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BIO-INSPIRED ADAPTIVE AUTONOMY FOR MOBILE VEHICLE TEAMS: RESULTS OF THE RESEARCH PROJECT 'GREX'

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ABSTRACT

In this paper we present a suggestion for the understanding of the term 'autonomy' in the research on mobile systems. The principle suggests an adapting level of autonomy that can always be changed to fit best to the concrete situation and mission task. It is described for the concrete usage in a research project dealing with teams of autonomous marine robots. Furthermore the proposal shows how the different team behaviors can be realized and various control schemes can be integrated. Finally, the presentation of results from the final sea trials of the project shows the successful conclusion and validates the results.

Index Terms – Mobile Robots, Marine Robots, Autonomous Underwater Vehicles, Autonomous Surface Crafts, Adaptive Autonomy.

1. INTRODUCTION – THE GREX-PROJECT

Within the European research project GREX[1], IUT and IST were two of in sum ten members of six different European states. The main purpose of the project was the creation of a conceptual framework and middleware systems to coordinate a team of heterogeneous marine vehicles, both surface crafts and underwater vehicles, which were delivered from different providers, to accomplish a predefined goal in an optimized manner by cooperation. This required the development of a control concept at team level to allow the different, already single autonomous vehicles to work together.

As a starting point, we used the concept of the Bio-inspired Adaptive Autonomy, which we published e.g. in [1]. In the next chapter, we explain how this concept suggests a new understanding of the term autonomy in mobile robotics and how it especially helps to realize teams of mobile robots. In chapter 3, the realization of the concept in the GREX project is described, before chapter 4 finally presents some results of the real sea trials.

[1] The project GREX (www.grex-project.eu, FP6-IST-2006-035223) was funded by the Sixth Framework Programme of the European Community.

2. DEFINITION OF BIO-INSPIRED ADAPTIVE AUTONOMY

In the current research on mobile systems, there is no exact definition of the term 'autonomy', although it is constantly used. The question arises whether a robot or a mobile system, which gets commands from outside during its mission, can be called 'autonomous'. It is also unclear whether an interaction of a human operator destroys the autonomy. In the field of teams of autonomous vehicles, it is actually an antilogy to speak about 'cooperating autonomous systems', as a system can either be cooperating or autonomous.

A solution of this problem can be the application of a certain concept of autonomy. Therefore, we developed the principle of 'Bio-Inspired Adaptive Autonomy'. That means the vehicles can operate in several different levels of autonomy, which are defined before the mission starts. These levels of autonomy can vary in arbitrary nuances in the overall spectrum. The opposed ends of the main spectrum are 'remote controlled' and '(total) autonomous'. Of course, both ends are allowed for the system's level of autonomy. In the spectrum between the ends, the vehicles are referred to as 'semi-autonomous'. It is important that the system is able to determine and change its level of autonomy during the mission on its own. An adapter realizes this functionality. The adapter chooses the current level of autonomy depending on situation and task (Figure 1). We published this concept e.g. in [1].

Using the described concept, the vehicles are able to respond to all possible changes in autonomy. In a team of several cooperating systems, this can be significantly reasonable. It allows the realization of different team behaviors using different methods, each optimally fitted to a concrete task. Additionally, the team can be designed to react on any unforeseen situations, like emergencies or the loss of a team member. So the vehicles can be called self-organizing platforms. The notation 'bio-inspired' was chosen due to the described principle which can also be noticed in biological systems.

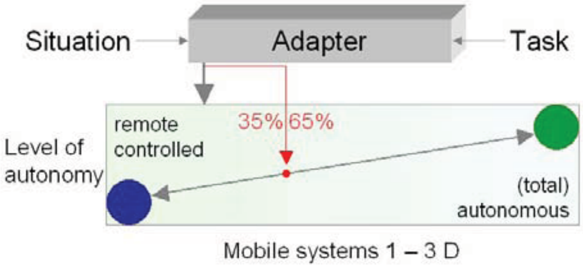

Figure 1: The concept of the adaptive autonomy

If a vehicle team is controlled with the concept of adaptive autonomy, it can react very quickly on changing situations at the place where the mission takes place. This can be a great advantage. It is not reasonable that a central computer has to confirm every action due to the communication's reaction time. In certain situations, the individuals have to react very quickly. Nevertheless, it is reasonable that certain decisions are made by higher instances. In general it can be stated that a higher instance has more cognitive abilities than the robots (a central computer with more calculating capacity or a human). Therefore, more time is required to involve a higher instance due to the dead time of the radio communication or the time that a human needs for his decision. That means the vehicles can react quickly, but with less accuracy. On the other hand higher instances are able to make more exact decisions, but they need more time to do so. This principle is comparable to the concept of cascaded control of the control theory, as shown in Figure 2.

A software adapter determines the current level of autonomy for each system in relation to the task and the current situation. One of the biggest challenges in this approach is the realization of the described adapter. Optimal adjusted levels of autonomy are a condition to reach good results in the execution of a mission.

3. AUTONOMY SPECTRUM IN THE GREX-PROJECT

As the vehicles participating in the GREX project were already single-autonomous, the challenge was to find a way to actually lower their level of autonomy in order to concentrate these decrements into a team instance which is an abstract term to symbolize the cooperation. IST and IUT developed a couple of so called Multi Vehicle Primitives (MVPs), where each one allowed for an individual realization and for different autonomy levels for the vehicles. E.g., there is one MVP called M_Init which performs the initialization at the beginning of a mission. Afterwards, a MVP M_GoToFormation (GTF) will be employed in order to guide the vehicles from their priory unknown starting positions to the desired

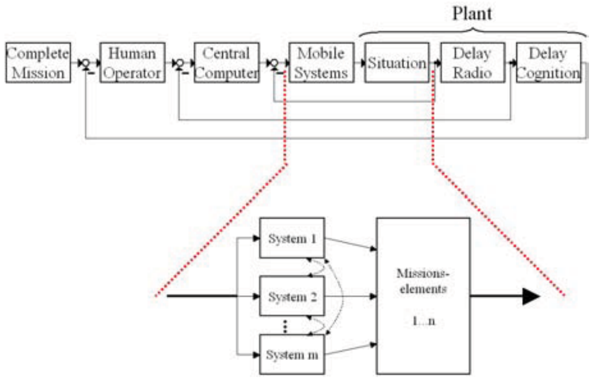

Figure 2: A swarm of mobile systems as a cascade control loop

formation (see [2]). A mixture of both, M_Final is used at the end of the mission to get the vehicles to desired positions and let them wait there. In-between, different mission parts can be executed, like M_CoordinatedPathFollowing (CPF), where the vehicles move along a defined trajectory while maintaining their formation (for measurements etc.). A proceeding was implemented according to [3] where vehicles perform path following and adapt their velocities on their own, only basing on position information from their team mates. In M_SearchingProcess (SePro), the same is performed, but a special termination procedure is employed when a certain condition is fulfilled, like the exceeding of a measurement value. In M_CooperativeTargetPursuit (CTP), a team of vehicles follows a defined moving (underwater) target and tries to keep a certain distance to it (see [4]).

The described principle of Adaptive Autonomy was realized by the implementation of different MVPs. In each case, the control scheme can be adapted to the concrete mission goals and the situation. A quantitative valuation can be added to the defined MVPs. This supports the comparison between different MVPs and the role the single vehicle has to perform. As a result, we got an autonomy spectrum.

This autonomy spectrum is directly linked to the functionalities realized within the GREX project. All functionalities and roles that the single vehicles have to perform are sorted according to the amount of autonomy they contain. Afterwards, real numbers between 0% (remote controlled) and 100% (totally autonomous) are added to allow for a quantification and graphical visualization. Therefore, these numbers should not be interpreted as absolute numbers, but as a ranking of the functionalities. E.g., a vehicle with an autonomy level of 80% is not 'twice as much autonomous' as a vehicle with a level of 40%. But it can be stated that the first vehicle is at a higher level of autonomy as the second one, while a vehicle with 60% is classified somewhere between them. That means, if new MVPs are defined within the GREX-application in the future, these may introduce new levels of autonomy. This will possibly change the current values of the autonomy levels, but not the existing ranking between them.

The borders of the autonomy spectrum are defined by the 0% and 100% levels of autonomy. The concrete definition of these borders may also vary for different applications, sorted by the single autonomous abilities of the vehicles. 100% will usually be the maximum level of autonomy which can be achieved from single vehicles. As described before, the vehicles have to lower their autonomy level to become a member of a team. So an autonomy level of 100% may, in some applications, contain complex behavior of a single vehicle, like mapping the environment on its own to use the map for navigation (SLAM – Simultaneous Localization And Mapping) or obstacle avoidance. For marine vehicles, usually a less complex behavior can be regarded as 100% autonomous. The vehicles that are used within the GREX project are regarded as 100% (single) autonomous, when they:

- execute a predefined mission plan on their own, whereas the mission plan consists of a trajectory to follow (lines and arcs) with attributive velocities, waiting maneuvers with fixed waiting times and/or activation/deactivation of sensors or other payload.
- do not change any of the parameters of the mission plan.
- possibly may cancel the whole mission according to a mission abort command which can be created internally or come from outside (operator, central computer).
- are not responsible for any activities of other vehicles/systems etc. and are not expected to create and communicate any kind of control commands.
- do not react on any control command coming from outside (except the mentioned mission abort, as most vehicles have a safety mechanism like this).

On the other side of the spectrum, a vehicle is regarded as 0% autonomous, when it is completely remote controlled by a human operator (or theoretically a computation instance from outside). The movement commands are sent by a console to the vehicle and executed immediately, without any checks or changes.

At the same time, the level of autonomy of the team instance can be defined which is at the same time a measurement for the cooperation achieved between the vehicles. When a number of vehicles operate in a state of 100% autonomy, there is no cooperation between them. If any of the vehicles lowers its own level of autonomy, it participates in a team by either overtaking a leader functionality (master) and creating commands for team mates or by overtaking a follower functionality (slave) and obey commands it receives from a leader via communication. Theoretically, it is possible that all vehicles lower their autonomy levels to 0% and become remote-controlled by the 'team instance' which then has the complete control about all vehicles on all levels. Of course it can be stated that solutions like that are far in the future, as long as they concern real vehicles. Also, this is not essentially the optimal state. Even if this solution might be possible, the single vehicles possibly are intended to remain several autonomous functionalities; this depends on their abilities and the situation. As a general rule it can be stated that it is reasonable not to aim for the highest level of autonomy (neither for the single vehicles nor for the team instance), but for the best fitting one.

The (cooperation) level of autonomy for the team instance is calculated as the sum of a decreases made in the single vehicles' autonomy levels, divided by the number of vehicles. Using this strategy, the cooperation level may vary between 0% and 100%. Let A_i be the level of autonomy of vehicle i of n, where the difference (100% - A_i) was transferred to the team. Then the cooperation level A_{Team} can be calculated as

$$A_{Team} = \frac{1}{n} \cdot \sum_{i=1}^{n} \left(1 - A_i\right) \tag{1}$$

Starting from this, autonomy levels were defined for the MVPs developed in the GREX project. Therefore, it is important how much autonomy the vehicles give away in each MVP. It must be mentioned that also vehicles that act as a leader and create commands for team mates lower the level of autonomy, as they accept responsibility for their mates and contribute to the cooperative behavior. Anyway, their autonomy levels will of course be higher than the levels of their mates which are under their command.

In M_Init, for instance, one vehicle is the leader and responsible for the coordination. All vehicles send an OK-statement to the leader, which then starts the mission execution. So within M_Init, the roles Coordination Master (CM) and Coordination Slave (CS) are existent. Also, coordination occurs in M_Final at the end of the mission as well as in M_SePro where the leader has to declare the termination of the primitive when a defined target has been detected.

In other primitives, there is also a leader which is able to create much more powerful replanning commands. In M_ GTF, M_Final, and M_CTP, the leader has to create new paths for its mates, while the mates have to accept these new mission paths. So two additional roles called Path Planning Master (PM) and Path Planning Slave (PS) are defined.

Finally, in several MVPs (M_CPF, M_SePro, M_CTP), the vehicles must establish a close formation by adapting their velocities. This is done by every vehicle on its own; there is no leader and no slaves. This functionality is called Formation Keeping (FK). It is no new role, but a condition which must or need not be fulfilled in the defined other roles, depending on the concrete MVP. In these specific primitives, the level of autonomy of all vehicles is

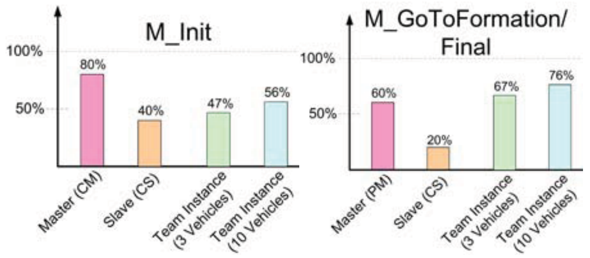

Figure 3 a & b: Levels of Autonomy and Cooperation for three selected Multi Vehicle Primitives (MVPs)

Table 1: Level of autonomy for the defined roles and functionalities

Notation	Level of Autonomy	Description
Totally autonomous	100%	Fulfils mission plan, accepts or creates no replanning
Coordination Master (CM)	80%	Leader, takes care of team mates
Path Planning Master (PM)	60%	Leader, takes care of team mates
Coordination Slave (CS)	40%	Slave, accepts (small) replannings
Path Planning Slave (PS)	20%	Slave, accepts (large) replannings
Tele-operated	0%	Remote controlled
Formation Keeping (FK)	-10%	Level of role is reduced by this amount

lowered by a fixed amount to stress that there is formation coordination between them.

The four defined roles need to be sorted between 100% and 0% autonomy. As stated above, a master has a higher level of autonomy as a slave. Additionally, the complexity of the performed replannings is an indicator for the amount by which the autonomy level is lowered. Like it was described before, a vehicle is at 100% autonomy as long as it does not create any replanning command at all. The more complex the replannings are, the more benefit is brought to the cooperation, and the autonomy level of the leader is reduced more. As a consequence, the Coordination Master (CM) must have the highest level of autonomy of the four roles. The Path Planning Master has the second highest level, as it creates more complex replanning commands and contributes more to the cooperation. Consequentially, the Path Planning Slave is assigned with the lowest autonomy level, as it has to accept the most complex replanning commands, while the Coordination Slave is located between PM and PS.

Table 1 shows the six defined roles and the FK-condition in the right sequence. At this point, the values from 100% to 0% for the level of autonomy are aligned to the roles, with equal distances between them. But, as stated above, the concrete values are not of importance, only the sequence. The equal distances between the four roles allow the easy definition of the value reduction by FK. As each of the roles has a distance of 20% to its direct neighbour, a value of 10% is chosen for FK which allows for definite results.

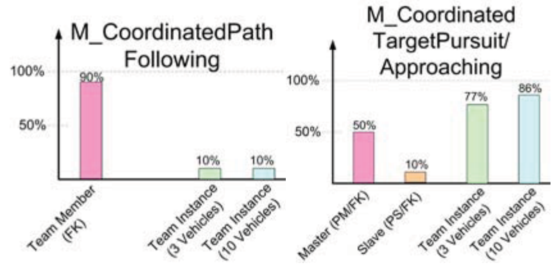

Figure 4 a & b: Levels of Autonomy and Cooperation for the MVPs M_CPF and M_CTP

Figure 3 shows the levels of autonomy and cooperation for the MVP M_Init. As shown in the table above, the levels of master and slave(s) are lowered to enhance the cooperation level, which depends on the number of vehicles according to equation (1). The same effect can be observed in Figure 3 b where the cooperation contains also path replanning for M_GTF and M_Final. Now the single levels of autonomy are even more lowered, which leads to a higher cooperation level. Note that in M_Final, both coordination and path planning are performed. For the determination of the autonomy level, Path Planning prevails as it causes the larger lowering.

If a single M_CPF is performed, there is no defined leader; also, no additional information is exchanged between the vehicles which remain in a high level of autonomy (Figure 4 a). M_SePro is a Coordinated Path Following, where additionally a master can stop the execution at all time, when the defined target was detected. So the vehicles are in the CM/CS-role, additionally they have to perform FK. That means the values result from those for M_Init, minus 10% for FK (not shown here). While the levels for M_SePro were constructed from those of M_Init and M_CPF, the values for M_CTP results from M_GTF and M_CPF, as in this case the master does not only determine the termination of the primitive, but he does also path replanning (see Figure 4 b).

It shall be stated again that the amount of the cooperation level is not an indicator of the quality reached by a solution. It is not the goal to raise this level as far as possible, but to find an optimal fitted one. For example, the cooperation level for CPF is very low, because the vehicles remain in a high autonomy level, executing pre-planned paths and change their velocity according to algorithms which run on their own hardware. This approach especially addresses the requirements for underwater vehicles where the limitations of acoustic communication need to be kept in mind. In CTP, one vehicle acts as the leader and is able to create new paths for its team mates, so the other vehicles are under its control. As the frequency of path replanning is much lower than the one of velocity change (and the needed exchange of position) and the proposed algorithm ensures that enough time it reserved for the acoustic communication to a dived AUV, the problems of

Table 2: Roles, Functionalities and Levels of Autonomy for the vehicles in the example mission

Vehicles	Delfim		DelfimX		SeaBee		Team Instance
MVP	R/F	LoA	R/F	LoA	R/F	LoA	LoA
Before Start	-	0%	-	0%	-	0%	0%
M_Init	CM	80%	CS	40%	CS	40%	47%
M_GTF	PM	60%	PS	20%	PS	20%	67%
M_CPF	FK	90%	FK	90%	FK	90%	10%
M_SePro	CS/FK	30%	CS/FK	30%	CM/FK	70%	57%
M_CTP	PS/FK	10%	PS/FK	10%	PM/FK	50%	77%
M_Final	PM	60%	PS	20%	PS	20%	67%
After Termination	-	0%	-	0%	-	0%	0%

Legend: R/F = Role / Functionality; LoA = Level of Autonomy

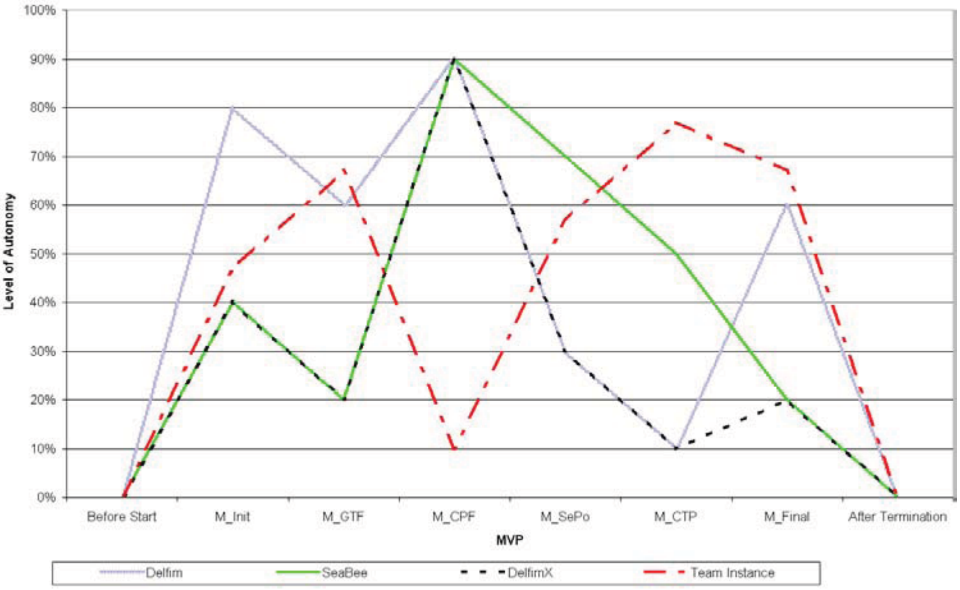

Figure 5: Levels of Autonomy during the example mission

communication could be solved here. The different levels for cooperation now state that the realization of both functionalities uses different structures, not that one solution is better than the other.

The statements of this chapter are depressed by an example of a mission with three GREX-vehicles Delfim and DelfimX (both surface crafts) and the autonomous underwater vehicle SeaBee.

The mission contains of an initialization process (M_Init) and a M_GoToFormation, both with Delfim as master. Afterwards, the vehicles move towards their mission area with M_CooperativePathFollowing. In the area, they perform an M_SearchingProcess to find a target sending an acoustic signal and a M_CooperativeTargetPursuit to follow it. In the last MVPs, the underwater vehicle is the master. At the end, a M_Final is used to end the process, again with Delfim as master.

Table 2 shows the roles / functionalities and the Levels of Autonomy for the single vehicles and the team instance, according to the principles described before. Prior to the mission start and after the termination, the vehicles are directly remote controlled by the human operator(s), so their own autonomy level as well as the one of team instance is at 0%.

Figure 5 shows a graphical display of the autonomy levels. It becomes clear: Whenever the vehicles lower their autonomy level, the one from the team instance rises, and vice versa. From the figure, it becomes clear how the control structure is organized for every vehicle, and which one is in the leading position. The figure also stresses the advantages of the concept of Adaptive Autonomy: Several different approaches for the control of autonomous marine vehicles have been developed and implemented within the GREX project. Each one is best fitted to the concrete task and situation it was developed for. Even during a single mission, the structures and functionalities of the vehicles in the team can change several times due to the usage of the Multi Vehicle Primitives. They are all comparable under the concept of Adaptive Autonomy.

4. RESULTS FROM SEA TRIALS

One of the results of the final sea trials of the GREX project in November 2009 in Sesimbra was the successful execution of a CLOSTT mission (Cooperative Line Of Sight Target Tracking, one of several developed solutions for M_CTP) where one or more tracking vehicles follow a defined target craft and establish a predefined distance to it. In the

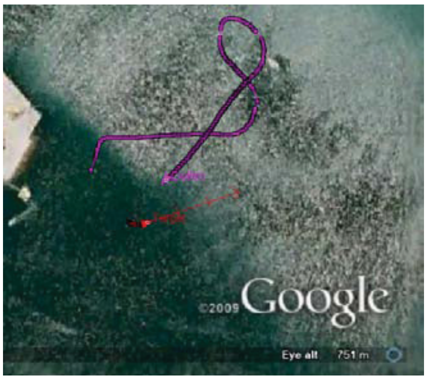

Figure 6: CLOSTT with one follower – part 1

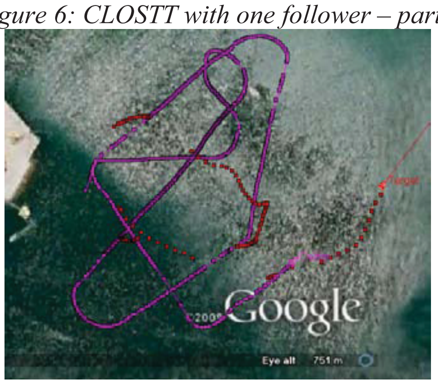

Figure 7: CLOSTT with one follower – part 2

Figure 8: Delfim and DelfimX of the Instituto Superior Técnico

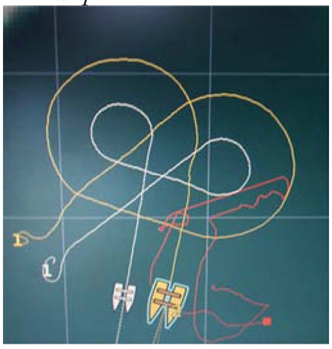

Figure 9: CLOSTT with two followers

implemented solution, the trackers do not try to follow the exact path of their target, but turn directly into its direction as soon as a new position is available. A part of the path is reserved as buffer to perform the replanning and send the new paths from the leading vehicle to the team members. The proposed solution was especially designed for the tracking of a dived target, which position can only be estimated with low frequencies, as explained in [4].

At first, a mission was performed, in which one vehicle (Delfim) had to follow a manually controlled SeaBee at the surface. Figure 6 and Figure 7 show the original position data of the vehicles. Delfim managed to follow the target vehicle on the base of regular transmission of the target position.

In a second run, the scenario was complicated. Now, the two vehicles Delfim and DelfimX followed a submerged buoy which was towed by a manned rubber boat, sending its position to the trackers via acoustic communication. Figure 8 shows the two catamarans on their mission. Figure 9 shows the real positions of the vehicles and the target during the mission. Additionally to the described path replannings using the CLOSTT-algorithm, the two catamarans also employed the CPF-algorithm to maintain their formation, so several coordination instances run in parallel.

5. CONCLUSION

The successful sea trials proofed the functionality of the developed control algorithms for cooperative behavior and of the control concept of 'Bio- inspired Adaptive Autonomy'. The realization of cooperation between heterogeneous marine vehicles, especially with an acoustic communication link in the loop, can be considered as a milestone in the research on unmanned mobile systems. These results will be a base for industrial usage as well as for further research activities.

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